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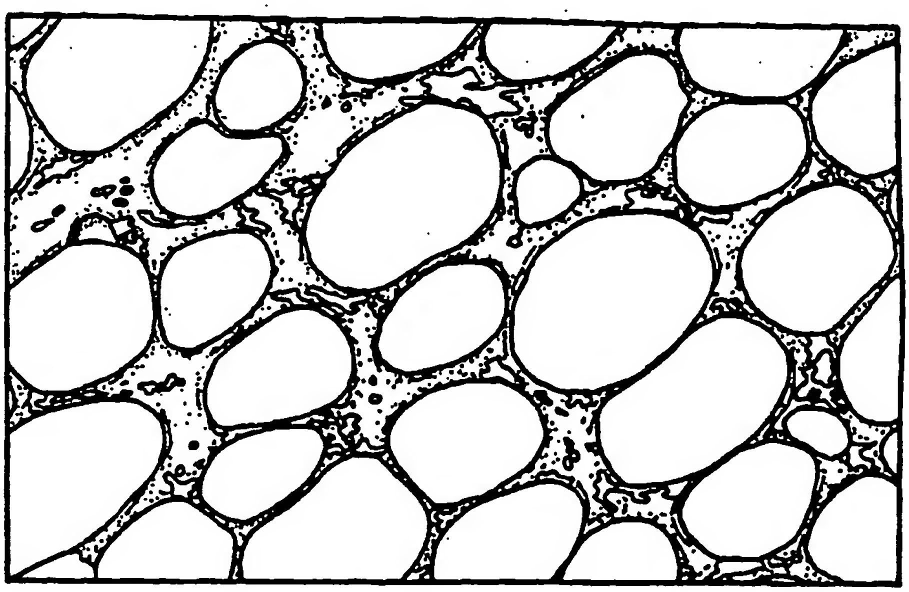
(54) Title: THERMALLY CONDUCTIVE CARBON FOAM



(57) Abstract

A thermally conductive, pitch derived carbon foam which when contacted with an evaporating liquid exchanges heat and therefore can be used as a heat exchanger. The foam is derived from mesophase pitch and has an open cell ligament composition. It can be employed in various types of cooling devices such as an air conditioner, a cold box, a cold pack, or a radiator.

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THERMALLY CONDUCTIVE CARBON FOAM

CROSS-REFERENCE TO RELATED APPLICATIONS

Not Applicable

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

The United States Government has rights in this invention pursuant to contract no. DE-AC05-96OR22464 between the United States Department of Energy and Lockheed Martin Energy Research Corporation.

Background Of The Invention

The present invention relates to a foam material derived from carbonaceous precursor, and more particularly to a thermally conductive, pitch-derived carbon foam having high thermal conductivity and heat exchanging properties.

The removal of unwanted heat is a frequently encountered problem. Conventional solutions include cooling fans, ice packs and refrigeration systems. In the latter, a working fluid is compressed (condensed) and pumped into an expansive chamber or pipe system where it evaporates, pulling heat from the atmosphere to satisfy its needed latent heat of vaporization, and thus cooling the surrounding environment. Air blown through the heat exchanger may be cooled and circulated to cool larger volumes such as in domestic and automotive air conditioning systems.

Active cooling (refrigeration) typically requires complex equipment including pumps, valves, compressors, etc. Many refrigeration systems require the use of CFCs (Freon), which is considered hazardous or environmentally unfriendly. An evaporative cooling system with a high thermal conductivity medium would offer a simpler, lower cost

alternative. There is a need for portable coolers which are lightweight and inexpensive so as to be deployed in the field or in third world countries.

The thermally conductive carbon foam of this invention overcomes the limitations of the prior art.

Summary Of The Invention

The general object of the present invention is to provide a thermally conductive carbon foam.

Another object is to provide a method of producing a cooling effect utilizing a thermally conductive carbon foam.

Yet another object is to provide a heat exchanging device employing a carbon foam core.

These and other objectives are accomplished in one embodiment by a thermally conductive, pitch-derived carbon foam.

In one aspect the foam has an open cell ligament composition.

In another embodiment, the objectives are accomplished by a method of producing a cooling effect wherein a thermally conductive, pitch-derived carbon foam is selected. The foam is contacted with an evaporating liquid, and an evaporation of the evaporating liquid is effected.

In still another embodiment, the objectives are accomplished by a heat exchanging device having a thermally conductive, pitch-derived carbon foam core. A fluid impermeable coating covers a portion of the foam core and exposes a portion. The exposed portion provides access and egress for an evaporating liquid.

In another aspect, there are upper and lower reservoirs in fluid communication with a core and a pumping device in fluid communication with the upper and lower reservoir adapted to deliver the evaporating liquid from the lower reservoir to the upper reservoir.

In still another aspect, the carbon foam is positioned in separate columns to provide a cold storage container with spacing between the columns.

In yet another aspect, relative motion between the foam and heat transfer fluid is developed in the presence or absence of an evaporative liquid by moving the foam, thereby accelerating evaporation and increasing the cooling effect.

Brief Description Of The Drawings

FIGS. 1-6 are micrographs of pitch-derived carbon foam graphitized at 2500°C and at various magnifications.

FIGS. 7-9 are charts plotting temperature/time of the carbon foam resulting from the evaporation of a working fluid according to this invention.

FIG. 10 is a diagrammatic view illustrating one embodiment employing the carbon foam of this invention.

FIGS. 11-14 are diagrammatic views illustrating other embodiments employing the carbon foam of this invention.

Detailed Description Of The Invention

A high thermal conductivity carbon foam is utilized to provide an evaporatively cooled heat sink or heat exchanger. The carbon foam is derived from mesophase pitch and has a ligament thermal conductivity approaching 700 W/m•K.

It is depicted in Figs. 1-6 and has an open structure which allows free access to a working fluid to the cell walls/ligaments. A preferred method for producing the carbon foam is described in a U.S. patent application entitled Pitch-Based Carbon Foam and Composition Serial No. _______, filed ________________________ and is commonly assigned. When the working fluid contacts the cell surface it evaporates, the latent heat of vaporization causes cooling of the carbon foam. The extent of cooling depends upon the working fluid and the ambient conditions (temperature and pressure). The heat sink/exchanger

temperature has been shown to fall to less than 223K (-50°C) using acetone as the working fluid at a pressure of 1200 microns Hg (1.2 torr), and 0.5°C using acetone as the working fluid at ambient temperature and pressure. Forced air flow over the carbon foam increases the temperature drop in excess of that observed under ambient conditions. The heat sink/exchanger described herein finds applications in heat removal systems such as personal/body cooling suits, portable refrigeration systems or coolers, and air conditioning systems (household and automotive).

The following Examples demonstrate the evaporative cooling effect on the previously described carbon foam when contacted with different working fluids as represented by acetone, ethanol and water. These Examples are not intended to limit the invention in any way. The foamed carbon was doused or partially immersed in the working fluid. Upon removal from the working fluid, and as indicated in Examples I-VI, the foam sample was placed in a vacuum furnace with a thermocouple penetrating the foam sample. The foam temperature was monitored as a function of time and pressure (vacuum). The ambient laboratory temperature was approximately 21°C.

EXAMPLE I: *Acetone*

Time(minutes)	Pressure(Torr)	Temperature(°C)
0	740	13.5
1	29	-37.5
2	29	-46.7
3	1.2	-51.8
4	1.2	-53.4

When the sample was removed from the vacuum furnace it was noted that ice had formed, presumably from moisture condensed from the furnace atmosphere, or desorbed from the foam.

EXAMPLE II: *Ethanol*

Time (minutes)	Pressure (Torr)	Temperature (°C)
0	740	20.5
1	29	5.3
2	29	-14.7
3	1.2	-21.7
4	1.2	-25.1
5	1.1	-26.8
6	1.0	-28.6

EXAMPLE III: *Water*

Time (minutes)	Pressure (Torr)	Temperature (°C)
0	740	20.5
1	29	16.4
2	29	16.5
3	29	16.6
4	29	14.6
5	29	12.9
6	29	10.5
7	29	2.6
8	29	-1.5
9	29	-5.5

In the instance of Example III the sample was immersed in water in vacuum to ensure that the foam was saturated. This probably allowed an excess of water to penetrate the sample and reduced the exposed foam surface area available for evaporation. Moreover, the resultant high water partial pressure in the furnace made it impossible to attain good vacuum in a reasonable time. Consequently, the experiment was repeated in Example IV, but with substantially less water applied to the foam.

EXAMPLE IV: *Water* (Repeat)

Time (minutes)	Pressure (Torr)	Temperature (°C)
0	740	19.9
1	29	14.5
2	29	0.3
3	29	-5.5

In this case, sub-zero temperatures were attained in a much shorter time than for Example III.

The data for Examples I, II and IV are plotted in Fig. 7. The lowest temperature observed (-53.4°) was attained in 4 minutes using acetone as the working fluid. Temperatures of -24.1°C and -5.5°C were attained over the same time period when the working fluid was ethanol and water, respectively.

A further series of tests as set forth in Examples V-VII were performed to show the effect of evaporative cooling at atmospheric pressure and temperature. The foamed carbon sample was placed in a petri dish. A thermocouple was located in a hole machined into the foam. The carbon foam was doused with the working fluid until the bottom of the petri dish was completely covered with the working fluid. The resultant foam temperature was then noted as a function of time.

Example V: *Acetone*

Time (minutes)	Temperature (°C)	Time (minutes)	Temperature (°C)
0	21.7	19	3.4
1	15.7	20	3.2
2	13.6	21	3.0
3	11.5	22	2.9
4	10.3	23	2.7
5	8.9	24	2.6
6	8.0	25	2.4
7	7.3	26	2.3
8	6.6	27	2.1
9	6.1	28	2.0
10	5.7	29	1.8
11	5.3	30	1.6
12	4.9	31	1.4
13	4.5	32	1.3
14	4.3	33	1.1
15	4.1	34	1.0
16	3.9	35	0.8
17	3.7	36	0.7
18	3.5	37	0.6
		38	0.5

After 38 minutes there was no acetone visible in the petri dish or under the carbon foam sample. The sample was placed in an air circulating oven at 60°C to dry it and then allowed to cool to ambient temperature.

EXAMPLE VI: *Ethanol*

Time (minutes)	Temperature (°C)	Time (minutes)	Temperature (°C)
0	21.6	19	15.4
1	20.3	20	15.3
2	19.6	21	15.1
3	19.0	22	15.0
4	18.6	23	15.0
5	18.1	24	14.9
6	17.8	25	14.8
7	17.4	26	14.8
8	17.1	27	14.8
9	16.9	28	14.7
10	16.7	29	14.7
11	16.5	30	14.6
12	16.3	31	14.6
13	16.2	32	14.6
14	16.0	33	14.5
15	15.8	34	14.5
16	15.7	35	14.4
17	15.6	36	14.4
18	15.5	37	14.4
		38	14.3

After 38 minutes there was a significant amount of ethanol visible in the bottom of the petri dish. The sample was placed in an air circulating oven at 60°C to dry it and then allowed to cool to ambient temperature.

EXAMPLE VII: Water

Time (minutes)	Temperature (°C)	Time (minutes)	Temperature (°C)
0	20.9	19	19.3
1	20.3	20	19.3
2	20.2	21	19.3
3	20.1	22	19.2
4	19.9	23	19.2
5	19.8	24	19.1
6	19.7	25	19.1
7	19.6	26	19.1
8	19.5	27	19.1
9	19.5	28	19.1
10	19.5	29	19.1
11	19.5	30	19.0
12	19.5	31	19.0
13*	19.5	32	19.0
14	19.4	33	19.0
15	19.4	34	18.9
16	19.3	35	18.9
17	19.3	36	18.9
18	19.3	37	18.9
		38	18.9

* Additional water squirted over carbon foam sample.

After 38 minutes there was a significant amount of water visible in the bottom of the petri dish. The ambient temperature and pressure data are plotted in Fig 8. The minimum temperatures are higher for all three working fluids than in the previous Examples where evaporation occurred under vacuum. Moreover, the rate of temperature decrease was much smaller for all three of the working fluid under ambient conditions. The lowest temperature reached (0.5°C) was attained in 38 minutes with acetone as the working fluid. The lowest temperatures attained over similar time periods were 14.3°C and 18.9°C for ethanol and water, respectively.

A third series of tests were conducted to determine effect on foam temperature of enhanced air flow during the evaporative cooling process. The procedure set forth in the previous Example was followed, except that in this series of experiments a fan (rotary, electric motor driven domestic

cooling type) was used to blow ambient air across the foam and petri dish.

EXAMPLE VIII: *Acetone* with forced air flow

Time (minutes)	Temperature (°C)	Time (minutes)	Temperature (°C)
0	21.5	4	-2.8
1	5.2	5	-3.2
2	-0.9	6	-3.5
3	-2.9	7	-3.7

Petri dish was frequently replenished with additional acetone.

EXAMPLE IX: *Ethanol* with forced air flow

Time (minutes)	Temperature (°C)	Time (minutes)	Temperature (°C)
0	21.1	6	9.1
1	14.6	7	8.9
2	11.5	8	8.7
3	10.8	9	8.8
4	9.7	10	8.9
5	9.3		

Ethanol in Petri dish replenished once.

EXAMPLE X: *Water* with forced air flow

Time (minutes)	Temperature (°C)	Time (minutes)	Temperature (°C)
0	21.1	8	15.0
1	18.7	9	14.9
2	17.1	10	14.8
3	16.5	11	14.8
4	15.9	12	14.7
5	15.6	13	14.7
6	15.3	14	14.7
7	15.1	15	14.6

The data from Examples VIII, IX and X are plotted in Fig. 9. An enhanced cooling effect is obtained when air is forced over the evaporating working fluid/carbon foam.

The Table below summarizes the temperature drops (differences) attained for each working fluid under the three sets of conditions employed.

Table. Summary of temperature drop data for the three conditions examined here.

Working Fluid	Temperature Drop, °C		
	Vacuum	Ambient pressure and Forced Air Flow	Ambient Pressure
Acetone	66.9	25.2	21.2
Ethanol	49.1	12.4	7.3
Water	26	6.5	2.0

The temperature drops recorded in the above Table for a vacuum represent extreme conditions. Lower temperature drops would be attained if intermediate vacuum pressures were used, as indicated by the ambient data. Forced air flow enhanced the cooling effect due to evaporation because the partial pressure of the evaporated solvent over the foam was reduced, and the saturated air was being constantly purged with fresh (unsaturated) air.

These data clearly demonstrate that the carbon foam of this invention readily attains very low temperatures, due to the evaporative cooling effect of the working fluid, which can be used for the removal of unwanted heat. The three example working fluids employed in the Examples were selected because of their availability. An ideal working fluid would have a high latent heat of vaporization, a vaporization temperature close to ambient, be non-toxic and environmentally acceptable.

The foam material of this invention attains low temperatures for several reasons: (i) It is an efficient heat transfer medium because of its excellent thermal

conductivity and large surface area; (ii) The working fluid has a high latent heat of vaporization and a low temperature (close to room temperature); (iii) The ambient pressure is low (i.e., a vacuum) causing rapid evaporation from the carbon foam surface.

The following are descriptions of preferred embodiments of heat removal systems for different applications that take advantage of the low temperature attained in the foam of this invention through evaporative cooling:

An evaporatively cooled heat sink or air conditioner for home or automobile is illustrated in Fig. 10 generally at 10. A working fluid is pumped from a reservoir 12 to a header tank 14 via pump 16 and lines 15 and 17. It drains through the carbon foam 18 of this invention which is encased in a impermeable coating or skin 20. The downward flow of fluid through the foam 18 occurs under the influence of gravity or a pressure differential created by a pump 16. Evaporation of the working fluid from the carbon foam surface causes cooling of the carbon foam 18. A vacuum in the reservoir 12 created by pump 16 enhances evaporative cooling from the foam 18 and increase the temperature drop, as demonstrated in the previous Examples. A fan with a motor 22 and duct 24 directs a separate air stream (at ambient temperature) from the air used for evaporation through penetrations 26 in the coating or casing 20 and foam core 18 where the air gives up excess heat to the cooled foam core 18. The air therefore exits the foam core 18 at below ambient temperature where it may be ducted to cool inhabited space. Condensers or cold traps 28 may be required to condense vapor exiting the foam core 18. The condensed working fluid is returned to the header tank 14.

Alternately, instead of air another cooling fluid, such as water, ethylene glycol, helium or nitrogen could be used to remove heat from critical components, such as electronics or chemical/medicines in cold storage, or internal combustion engines.

Fig. 11 shows an evaporatively cooled cold box generally 30. An encapsulated carbon foam core 32 surrounds a series of open cavities 36 into which items to be cooled are placed. The encapsulating skin 38 also provides enclosed cavities 40 and 42 above and below the foam core 32. The working fluid is poured into the top closed cavity 40 such as through opening 44 and drains through the foam 32. Vents 46 are additionally located in the top cavity allowing the working fluid to evaporate to the atmosphere. Evaporation of the working fluid from the carbon foam 32 surface reduces the foam's temperature. Heat for additional working fluid evaporation is extracted from the open cavities 36, thus reducing the temperature within the cavities. The entire cold box is wrapped or clad in the thermal insulation and a thermally insulated lid 48 seals the open (cold storage) cavities. A fan could be fitted to the insulated cold box 30 to increase air flow through the foam and thus increase the evaporation rate of the working fluid.

An evaporatively cooled cold pack could also be made with the carbon foam. It would be somewhat similar to those currently available that are frozen prior to use, and may be fabricated using the carbon foam material. A carbon foam block would be encapsulated with a impermeable material. The working fluid would be poured in, wet the foam surface and evaporate, causing the foam temperature to drop. An opening through which the working fluid would be poured would also allow the evaporating fluid to vent to atmosphere.

Fig. 12 shows the carbon foam 18 of this invention in the form of a block 51 to be used as an automobile radiator generally 50. Hot engine cooling fluid is introduced into intake manifold 52 connected to pipes 54 which pass through the foam block 51 to the output manifold 56. As seen in Fig. 13 foam block 51 is supported in an automobile as indicated at 58 having the usual frame 53 and wheels 55. Hot fluid is conveyed by output conduit 57 from engine 59 to

intake manifold 52. Cooled fluid returns to engine 59 by intake conduit 60 from output manifold 56. As the automobile 58 is moving down the road, air is forced through the foam block 51 and removes the heat to the environment. The efficiency of heat transfer from the radiator 50 to the ambient air is directly related to the surface area of the block 51. Since a foam block 2 feet by 2 feet by 1 inches has approximately 19,000 m^2 of surface area while a typical radiator may approach 10 m^2, the increased efficiency of the radiator will improve by roughly 3 orders of magnitude.

Fig. 14 shows the carbon foam 18 in the form of a spinning disk device generally 70. The disk device includes a foam disk portion 72 connected with a double walled conduit 74 providing a central hollow conduit member 76 and an outer conduit member 78. Air and an evaporative fluid are introduced into conduit 78 where it passes into the foam disk portion 72. The air and evaporative fluid are spun out of the disk portion 72 as it is rotated to the outside of the disk portion 72. This is shown by arrow 80 for the air and arrow 82 for the evaporative liquid. A fluid impermeable coating 79 provides a sealed surface on opposing sides of the disk portion 72. Hot fluid to be cooled is passed down central hollow conduit member 76 where it is cooled in disk portion 72. It flows out the bottom of conduit 76 as indicated at 84. The spinning disk portion 72 is supported by the bearings 86 and 88 in a suitable housing. Rotation of disk portion 72 is effected by motor 90 driving pulleys 92 and 94 by drive belt 96 with pulley 94 connected to conduit 74.

It will thus be seen that through the present invention there is provided:

(i) A carbon foam having a very high thermal conductivity. Large temperature gradients are thus unlikely to develop, and the surface cooling due to evaporation will be quickly translated to bulk material cooling.

(ii) The foam has an extended surface area resulting from its cellular structure. This allows for rapid evaporation of the working fluid.

(iii) The foam has an open structure which allows the working fluid to permeate the material.

(iv) The cell size and ligament properties may be varied, allowing the material to be tailored to the selected working fluid or anticipated cooling application.

(v) A working fluid may be selected that is non-toxic and environmentally acceptable.

(vi) Evaporative cooling systems such as those disclosed herein potentially offers low (zero) energy consumption and increased reliability with few or no moving parts.

CLAIMS

What is claimed is:

1. A thermally conductive, pitch derived carbon foam.

2. The foam of claim 1 having a foam ligament conductivity of about 700 W/m•K.

3. The foam of claim 1 having an open cell structure.

4. A method of producing a cooling effect comprising:

selecting a thermally conductive, pitch derived carbon foam; and

contacting said foam with an evaporating liquid to effect an evaporation of said evaporating liquid and a cooling of said carbon foam.

5. The method of claim 4 wherein said evaporating liquid is acetone.

6. The method of claim 4 wherein said evaporating liquid is ethanol.

7. The method of claim 4 wherein said evaporating liquid is water.

8. The method of claim 4 wherein said evaporation is caused by subjecting said foam and said evaporating liquid to a vacuum.

9. The method of claim 4 wherein said evaporation is caused by subjecting said foam and said evaporating liquid to a moving air stream.

10. The method of claim 4 wherein said evaporation is caused by moving said foam through an air stream.

11. A heat exchanging device comprising:

a thermally conductive, pitch derived carbon foam core; and

a fluid impermeable coating covering a portion of the foam core and exposing at least one portion thereof providing access and egress for an evaporating liquid.

12. The heat exchanging device as defined in claim 11 further including upper and lower reservoirs in fluid communication with said core; and

a pumping device in fluid communication with said upper and lower reservoir adapted to deliver said evaporating liquid from said lower reservoir to said upper reservoir.

13. The heat exchanging device of as defined in claim 12 further including a fan member adapted to direct air into the said foam core.

14. The heat exchanging device as defined in claim 11 wherein said carbon foam is positioned in separate columns to provide a cold storage container with spacing between the columns.

15. A heat exchanging device comprising:

a thermally conductive, pitch derived foam core;

means to move said core through atmospheric air;

an intake manifold for introducing fluid to be cooled into said core; and

an output manifold for receiving cooled fluid from said core.

16. The heat exchanging device of claim 15 connected to an automobile.

17. A heat exchanging device comprising:

a thermally conductive, pitch derived core in the form of a disk;

an air intake conduit and an evaporative liquid intake conduit in fluid communicator with said disk;

a conduit for receiving fluid to be cooled in fluid communication with said disk;

a conduit for conveying cooled fluid from said disk; and

means to support and rotate said disk.

18. The heat exchanging device of claim 17 wherein said conduit for receiving fluid to be cooled and conveying cooled fluid from said disk are the same.

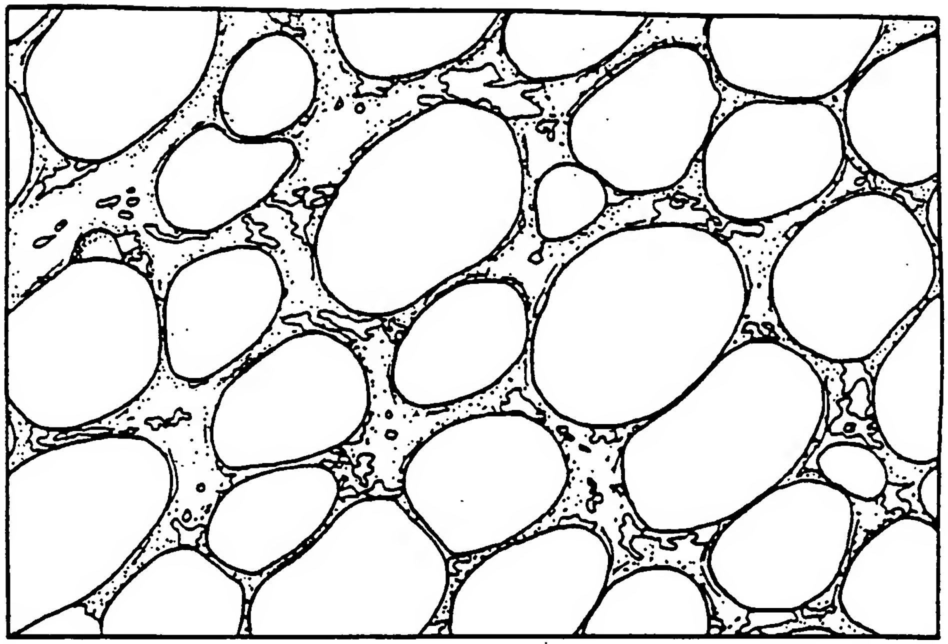


FIG. 1

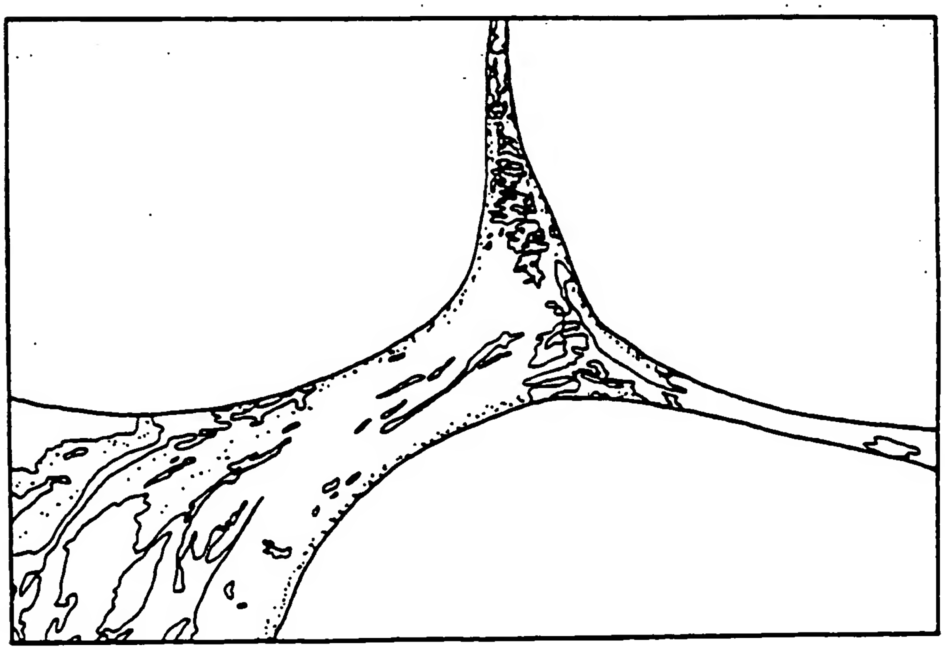


FIG. 2

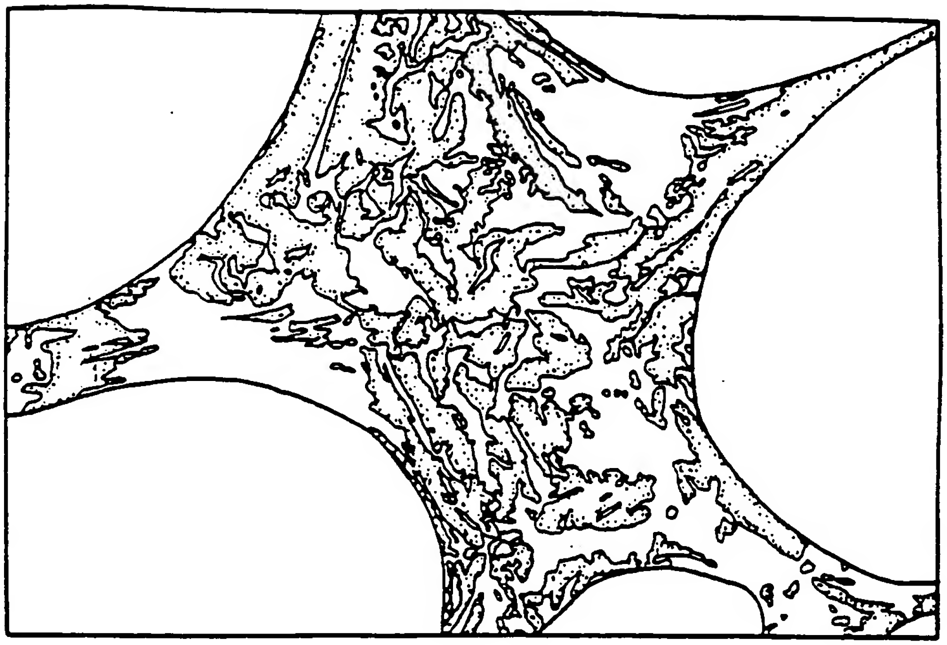


FIG. 3

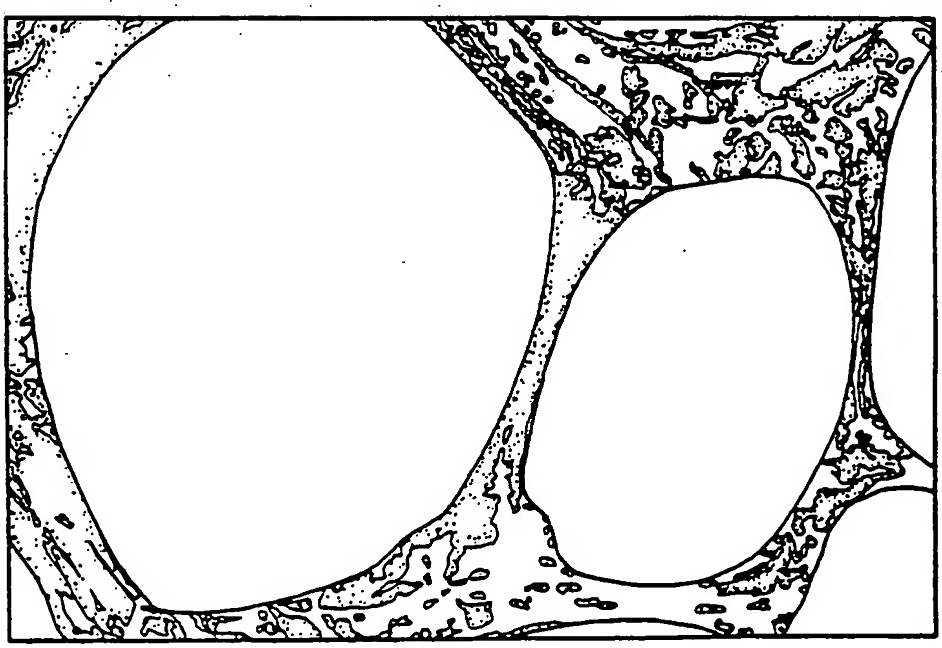


FIG. 4

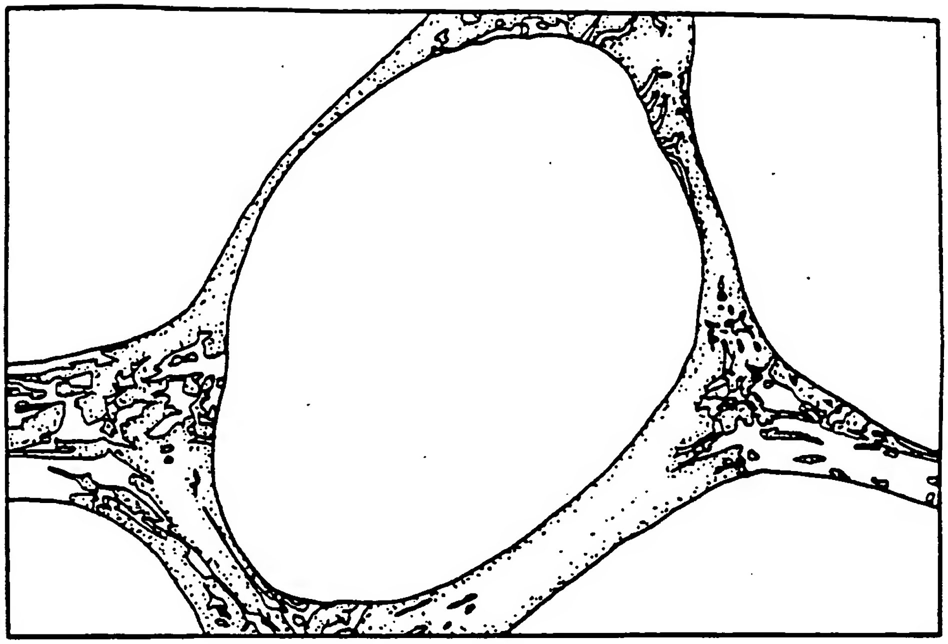


FIG. 5

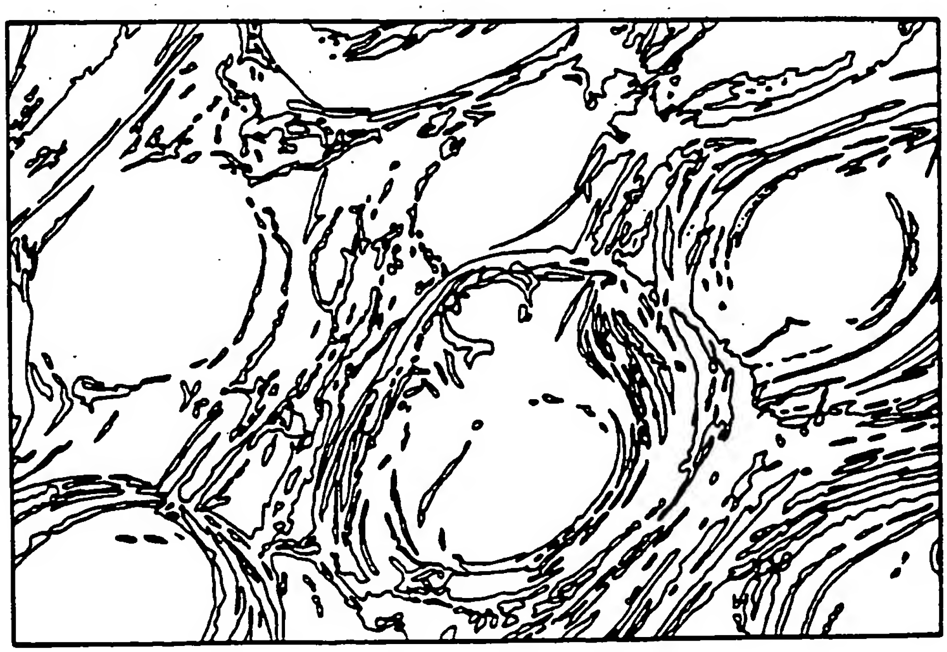
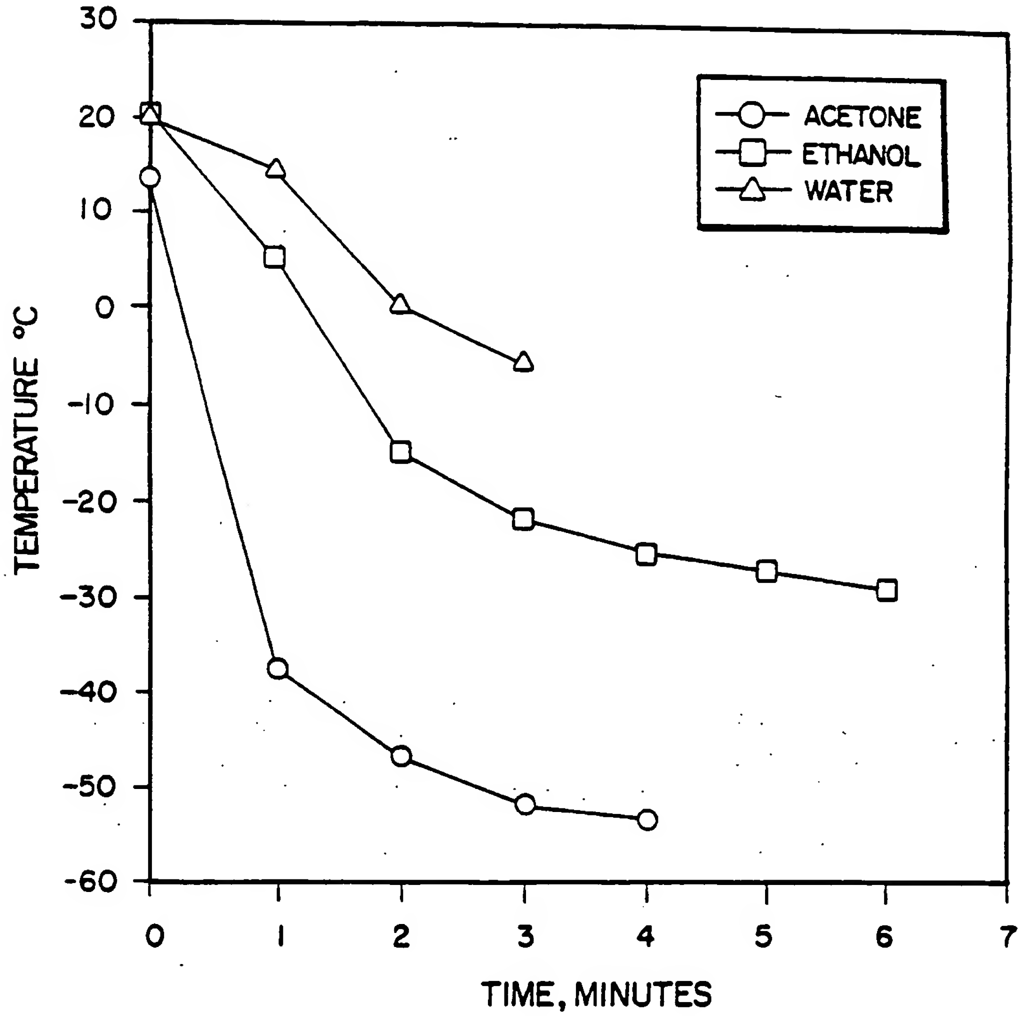


FIG. 6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WATER

FIG. 7

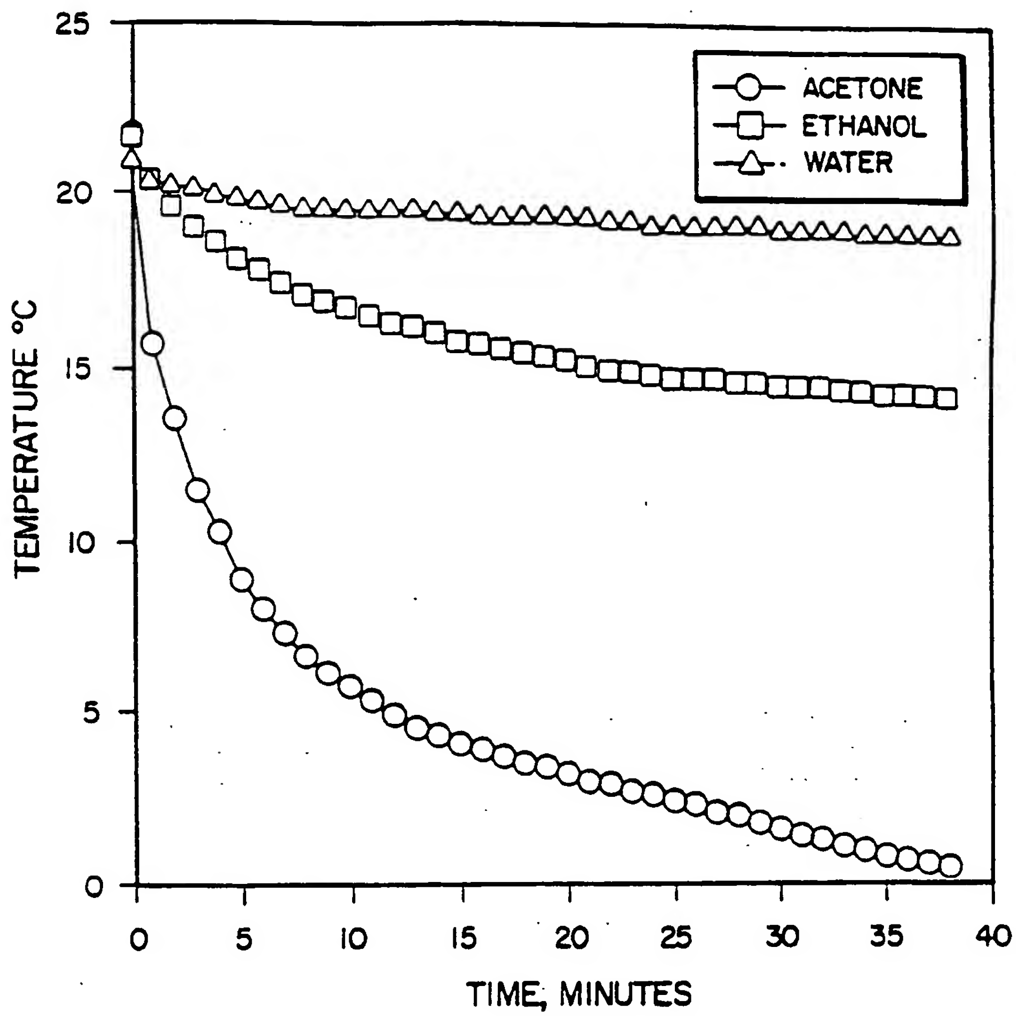
25
20
15
10
5
0
TEMPERATURE °C
0
5
10
15
20
25
30
35
40
TIME, MINUTES
ACETONE
ETHANOL
WATER

FIG. 8

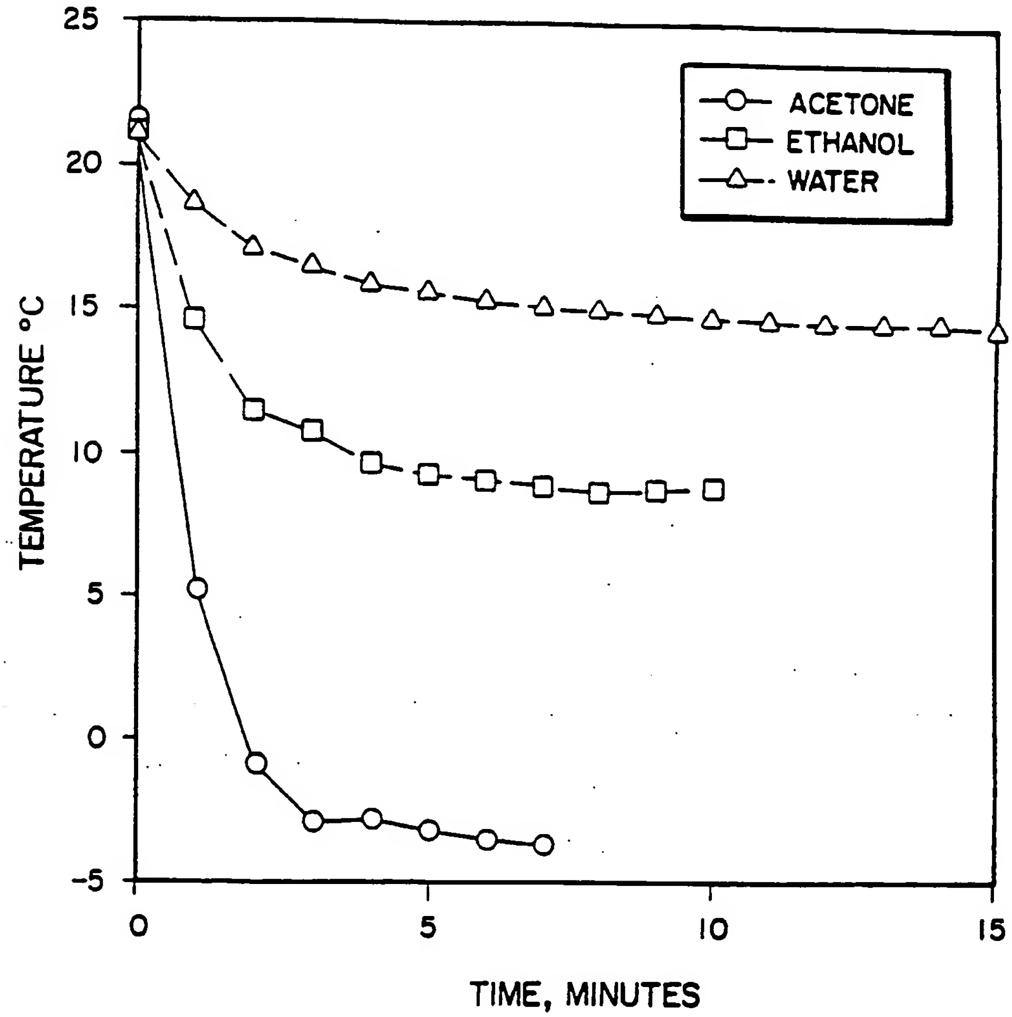
25
20
15
10
5
0
-5
TEMPERATURE °C
0
5
10
15
TIME, MINUTES
ACETONE
ETHANOL
WATER

FIG. 9

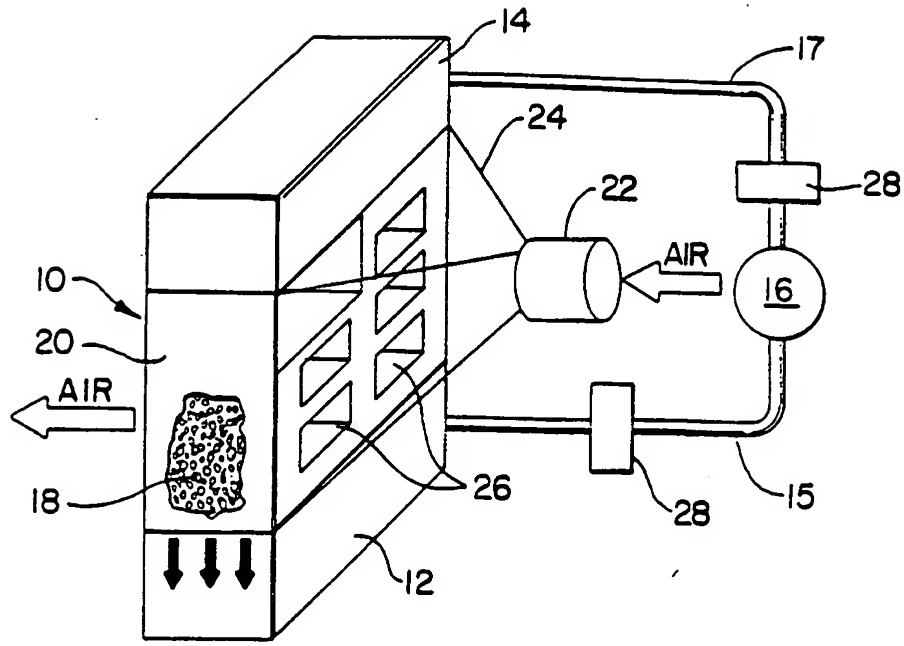
14
17
24
22
28
AIR
16
10
20
AIR
18
26
28
15
12

FIG. 10

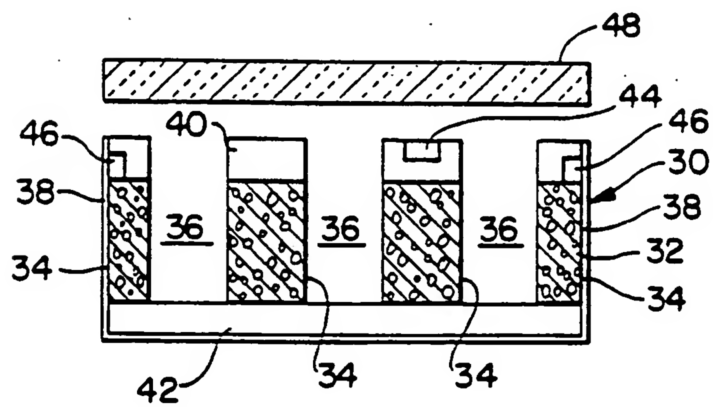
48
44
46
40
46
30
38
36
36
36
38
32
34
34
42
34
34

FIG. 11

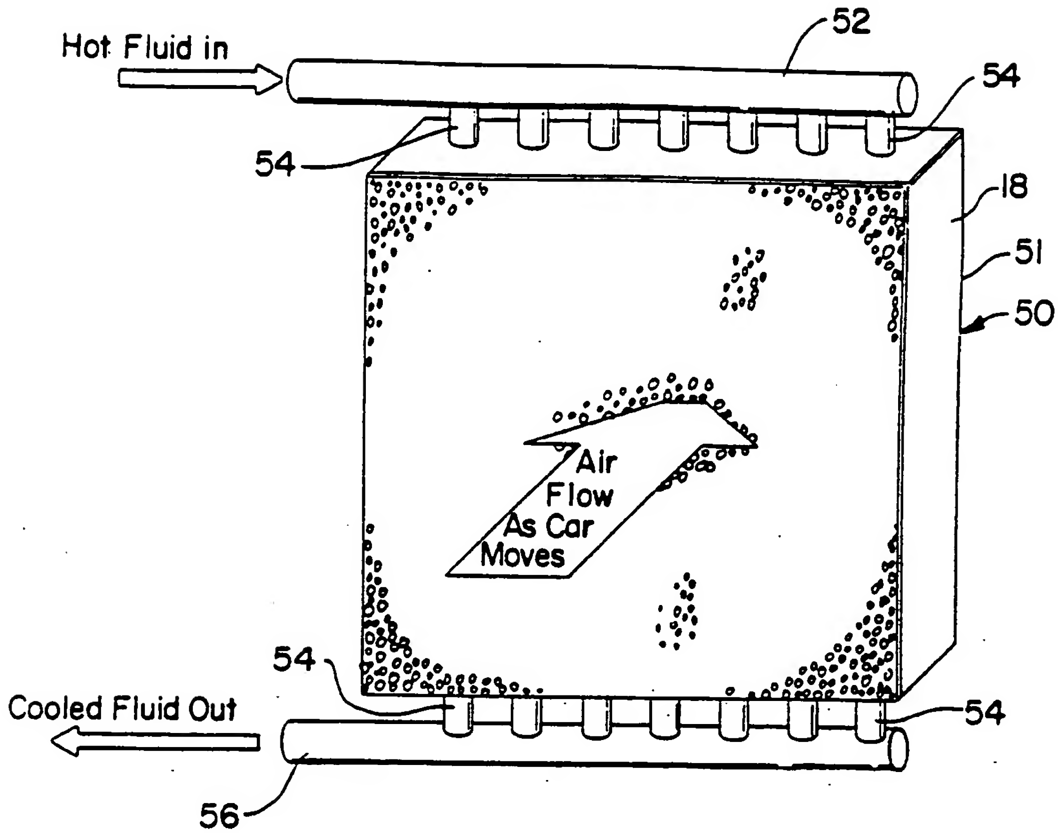
Hot Fluid in
52
54
54
18
51
50
Air
Flow
As Car
Moves
54
Cooled Fluid Out
54
56

FIG. 12

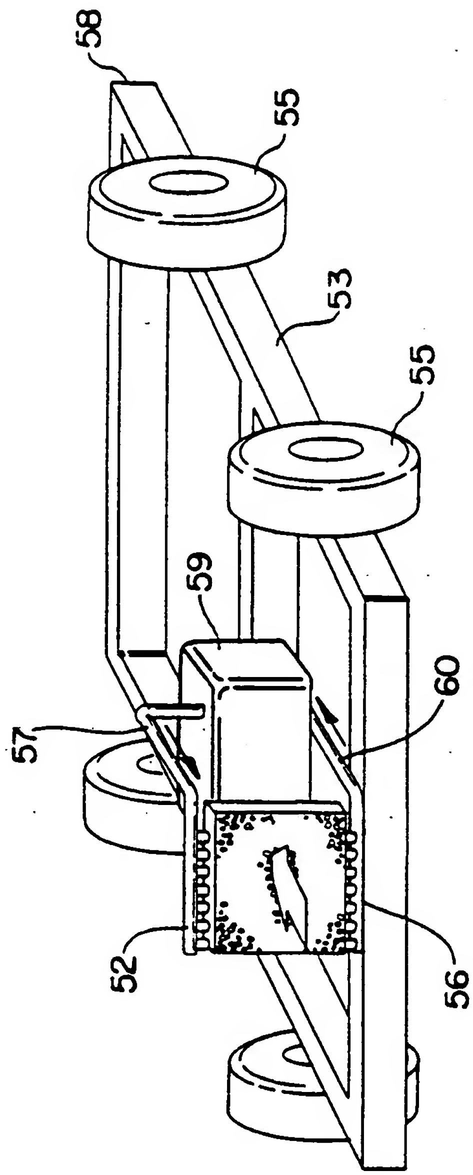

FIG. 13

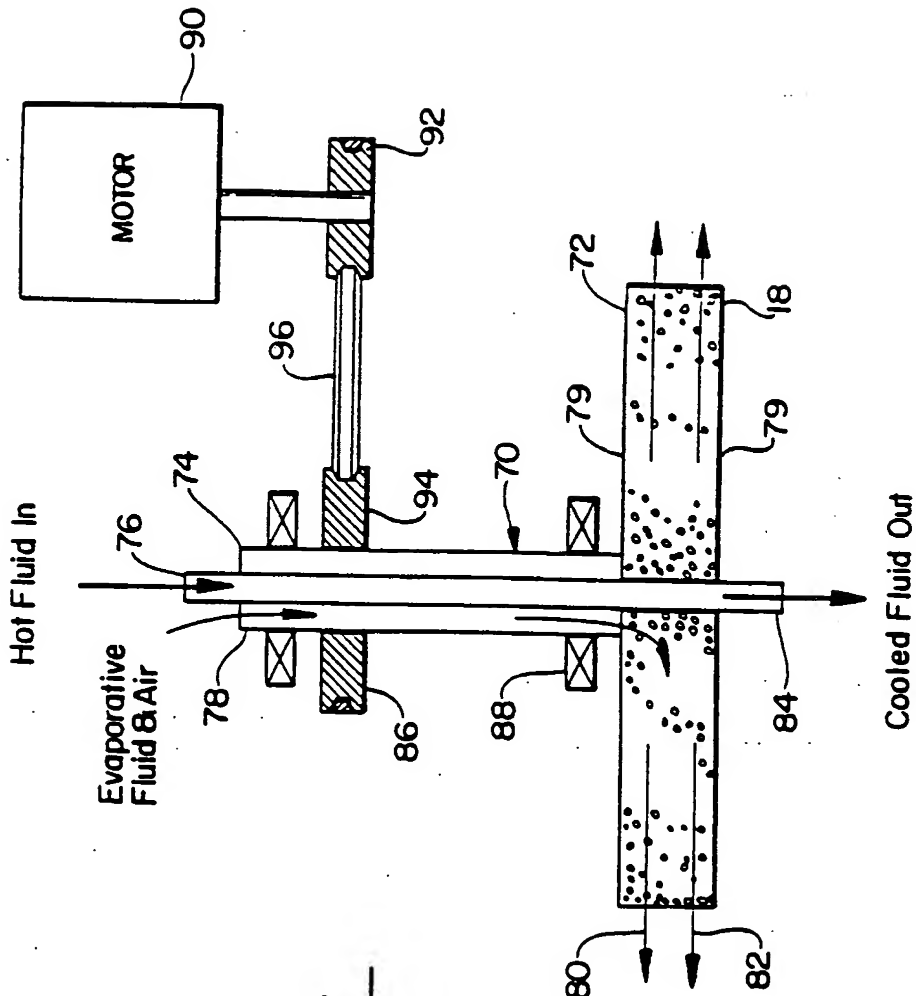
MOTOR
90
92
96
94
74
76
70
72
18
79
79
Hot Fluid In
Evaporative
Fluid & Air
78
86
88
84
Cooled Fluid Out
80
82

FIG. 14